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# Optimization of $Pr^{3+}$:ZBLAN Fiber Amplifiers

B. Pedersen, W. J. Miniscalco, and R. S. Quimby

*Abstract*—**Experimental parameters have been measured and used in a quantitative model of $Pr^{3+}$-doped fluorozirconate fiber amplifiers. The optimum cutoff wavelength was determined to be 800 nm and the gain for 400 mW of pump was found to increase from 12 to 34 dB if the NA was increased from 0.15 to 0.25. Lengthening the metastable state lifetime from 110 to 300 μs would significantly improve amplifier performance while concentration quenching can appreciably degrade it.**

## Introduction

Recently, $Pr^{3+}$-doped fluorozirconate fiber amplifiers have been demonstrated to provide gain in a broad band centered on the 1300-nm window [1]-[3]. Net gains of $\approx 30$ dB have been achieved, but the low quantum efficiency of the $^1G_4$ upper level in the gain transition leads to very high pump power requirements [4], [5]. Although experiments have revealed the importance of waveguide parameters in reducing the required pump power, until now there has not been a systematic analysis of the performance improvements that can be achieved through fiber design or the use of host glasses providing a longer lifetime for the metastable state. To this end we have examined the effects of cutoff wavelength, numerical aperture (NA), and $^1G_4$ lifetime ($\tau$) on the performance of $Pr^{3+}$-doped fluorozirconate fiber amplifiers operated in the small-signal regime. The quantitative numerical model used included excited state absorption (ESA) and ground state absorption (GSA) at the signal wavelength as well as the full spectrum of amplified spontaneous emission (ASE) at the signal and pump wavelengths. The calculated small-signal gains are in good agreement with recent experimental results and indicate that further improvement can be obtained.

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## Model for $Pr^{3+}$-Doped Fibers

Fig. 1 illustrates the relevant energy levels and transitions included in the calculation. Level $^1G_4$ is excited directly by pumping from the $^3H_4$ ground state, and gain at $\approx 1310$ nm is obtained by stimulating the $^1G_4 \rightarrow {}^3H_5$ transition. However, the $^1G_4 \rightarrow {}^1D_2$ transition produces an ESA band peaking at $\approx 1380$ nm and has a short wavelength tail down to $\approx 1290$ nm. An additional problem is the $^3H_4 \rightarrow {}^3F_4$ transition that peaks at $\approx 1440$ nm and leads to ground state absorption of the signal for $\lambda \geq 1290$ nm. Fig. 2 shows the cross sections for the transitions indicated by arrows in Fig. 1. The GSA cross sections were determined from absorption measurements on bulk $Pr^{3+}$-doped ZBLAN samples. The stimulated emission and ESA cross sections at the signal wavelength are those reported by Quimby and Zheng [6]. The stimulated emission cross sections at the pump band ($\approx 1050$ nm) were obtained from a McCumber analysis [7] and scaled using the radiative rate of Ohishi *et al.* [1]. The numerical model is based on one used previously for $Er^{3+}$-doped fiber amplifiers [8], which was adapted to the steady state rate equations for the excited $^1G_4$ state and the ground $^3H_4$ state. The resulting model is almost equivalent to the two-level model for $Er^{3+}$-doped fiber amplifiers pumped at 1480 nm, except for the fact that at the signal wavelength one must consider ESA and the GSA of the signal does not contribute to the population in the upper laser level. The

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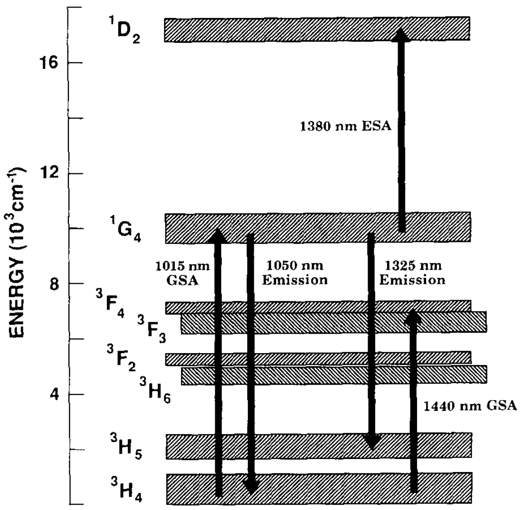


Fig. 1. Energy level diagram for $Pr^{3+}$ with relevant transitions illustrated by arrows.

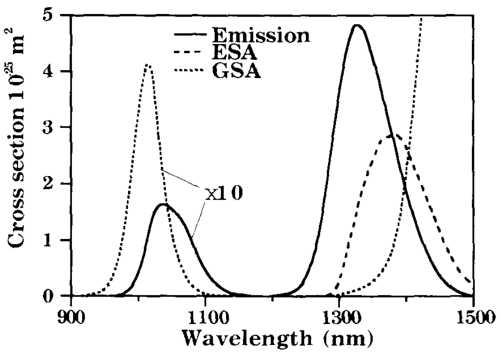


Fig. 2. Cross section spectra for the transitions included in the model.

model includes the wavelength-dependent ASE around 1310 and 1050 nm.

To verify the model, we used the fiber parameters for a $Pr^{3+}$:ZBLAN amplifier reported by Miyajima *et al.* [5], and compared the calculated to the measured results. Fig. 3 plots the small-signal gain as function of pump power for a fiber with 2000 ppm-wt $Pr^{3+}$, cutoff wavelength of 1260 nm, an NA of 0.41, and length of 8 m [5]. Note that the measurements lie above the theoretical curve. This results from the experimental points being determined by adding $\approx 6$ dB of fiber loss to the net fiber gain [9]. Of this $\approx 0.75$ dB/m loss, 0.6 − 0.7 dB/m corresponds to GSA from the $Pr^{3+}$ $^3H_4 \rightarrow {}^3F_4$ transition, consistent with our calculated value of 0.7 dB/m at 1310 nm. As was pointed out by Ohishi *et al.* [4], this GSA should not be added to the observed gain to determine the fiber gain since it represents loss due to unexcited ions which is bleached in a highly excited amplifier. Accordingly, to obtain the true fiber gain the experimental values reported must be reduced by $\approx 6$ dB, bringing them into agreement with the calculation. We also simulated the experimental results reported by Ohishi *et al.* [4]. The inset in Fig. 3 displays gain versus signal wavelength for 925 mW of pump power at 1017 nm. Here the fiber is doped with 500 ppm-wt $Pr^{3+}$, has a cutoff wavelength of 650 nm, an NA of 0.16, and a length of 23 m [4]. The crosses are the experimental results [4], and the solid curve is the calculations. The good agreement observed between calculations and measurements gives us confidence that the model can be used in a quantitative analysis of $Pr^{3+}$-doped fiber amplifiers.

## Analysis

We have used the model to quantitatively examine the effects of waveguide design and $^1G_4$ lifetime for $Pr^{3+}$-doped ZBLAN fiber amplifiers. Initially the small-signal gain at 1310 nm was calculated for step-index fibers pumped codirectionally at 1017 nm for several pump powers. The fiber NA's ranged from 0.2 to 0.5 and the results indicated that the optimum cutoff wavelength was $\approx 800$ nm and was almost independent of the NA and pump power. Fig. 4 plots the small-signal gain versus the NA for codirectional pumping with four different pump powers and the optimum cutoff wavelength of 800 nm. Each point on the curves is for the fiber length giving maximum gain. Scattering loss in the fiber has been ignored since it is typically $\approx 0.1$ dB/m with prospects for still further improvement. The gain increases with increasing NA due to the improved overlap between the $Pr^{3+}$ ions and the pump and signal modes. For 50 mW of pump power gains higher than 10 dB may not be practical since the NA would have to be $> 0.4$. For pump powers of 100 and 200 mW the gain increases almost linearly with NA for NA < 0.35. For 400 mW of pump powers the biggest improvement is found when increasing the NA from 0.15 to 0.25, which roughly triples the gain in dB. It is observed that the gain curves bend over for high NA's. This is because the amplifier is saturated by ASE around 1310 nm.

The efficiency of $Pr^{3+}$:ZBLAN fiber amplifiers is limited by the low quantum efficiency of the metastable state. The $^1G_4$ level experiences rapid nonradiative decay to the $^3F_4$ through multiphonon emission, leading to an observed lifetime of 110 $\mu$s compared to a radiative lifetime of 3.2 ms [1]. The nonradiative relaxation rate of the $^1G_4$ can be decreased through the use of other glass hosts with either a lower effective phonon frequency or weaker electron-phonon coupling. We have examined the potential improvement in amplifier performance that could be realized through the resultant increase in lifetime $\tau$ of the metastable state. Fig. 5 plots the small-signal gain as function of $\tau$ for pump powers of 100 and 250 mW. The calculations used the cross sections for $Pr^{3+}$:ZBLAN and represent the effect of changing only the nonradiative rate. For the conditions examined, the gain is very sensitive to $\tau$ for $20 < \tau < 400$ $\mu$s. If $\tau$ could be increase to 300 $\mu$s without changing the cross sections, only 100 mW of pump power would be required to obtain 30 dB gain compared to 250 mW for $Pr^{3+}$:ZBLAN at room temperature. As a result of cross relaxation, the lifetime of the $^1G_4$ decreases with increasing $Pr^{3+}$ concentration above $\approx 1000$ ppm-wt for fluorozirconate glasses [4]. Fig. 5 also illustrates how using higher concentrations to reduce the fiber length and associated scattering loss will reduce the gain. The

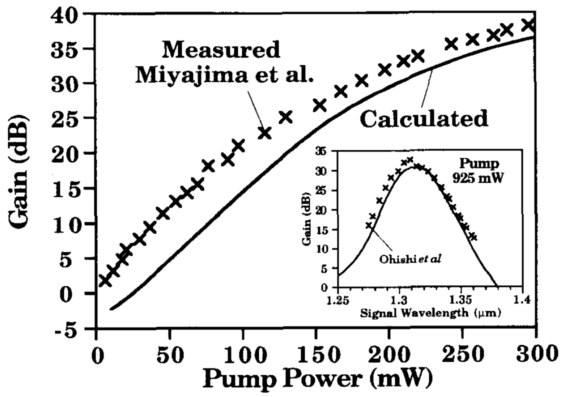


Fig. 3. Gain versus launched pump power. Crosses are measurements reported by Miyajima *et al.* [5]. The solid curve is simulations. Inset: gain versus signal wavelength. Crosses are measurements reported by Ohishi *et al.* [4], and the solid curve is simulations.

degradation is seen to be quite severe: cutting the lifetime in half will cut the gain in dB by a factor of two. As in Fig. 4, the gain curve bends over due to ASE.

## Conclusion

A model has been developed for $Pr^{3+}$-doped fiber amplifiers that provides small-signal gains in good agreement with reported experimental results. It has been used to optimize waveguide design and predicts an optimum cutoff wavelength of 800 nm for step-index fibers that is insensitive to NA and launched pump power. For 50 mW of pump power, gains $>10$ dB can be obtained only for NA's $>0.4$. For pump powers $\leq 200$ mW and NA's $<0.35$, the small-signal gain in dB increases linearly with the NA. For 400 mW of pump power the gain can almost be tripled by increasing the NA from 0.15 to 0.25. Increasing the metastable state lifetime to 300 $\mu$s would reduce to pump power required to achieve 30 dB gain from 250 to 100 mW.

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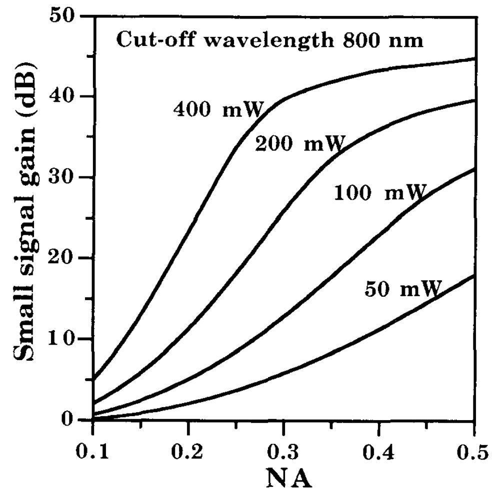


Fig. 4. Small-signal gain versus NA for step index fibers and codirectional pumping. The signal wavelength is 1310 nm and the pump wavelength is 1017 nm.

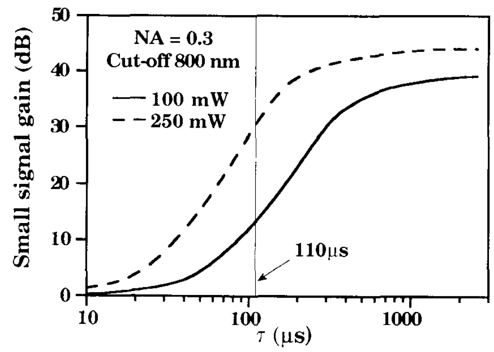


Fig. 5. Small-signal gain versus the observed lifetime, $\tau$, for the $^1G_4$ level. The launched pump powers are indicated.

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